

# A GW Observatory Operating Beyond the Quantum Shot-Noise Limit: Squeezed Light in Application

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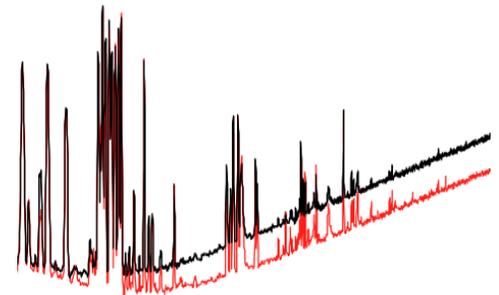
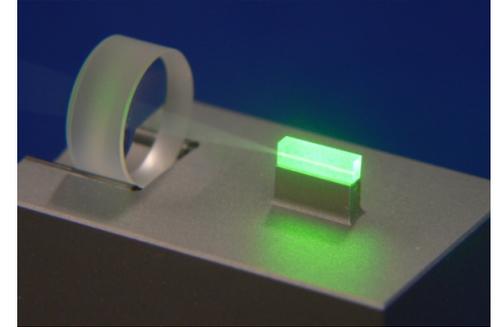
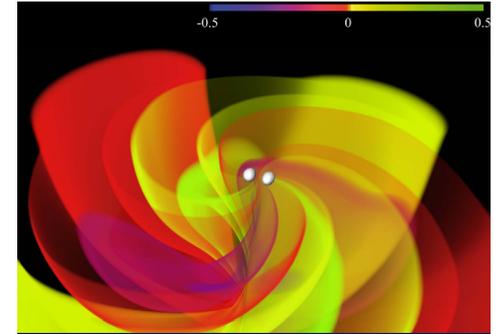
Institut für Gravitationsphysik

Leibniz Universität Hannover

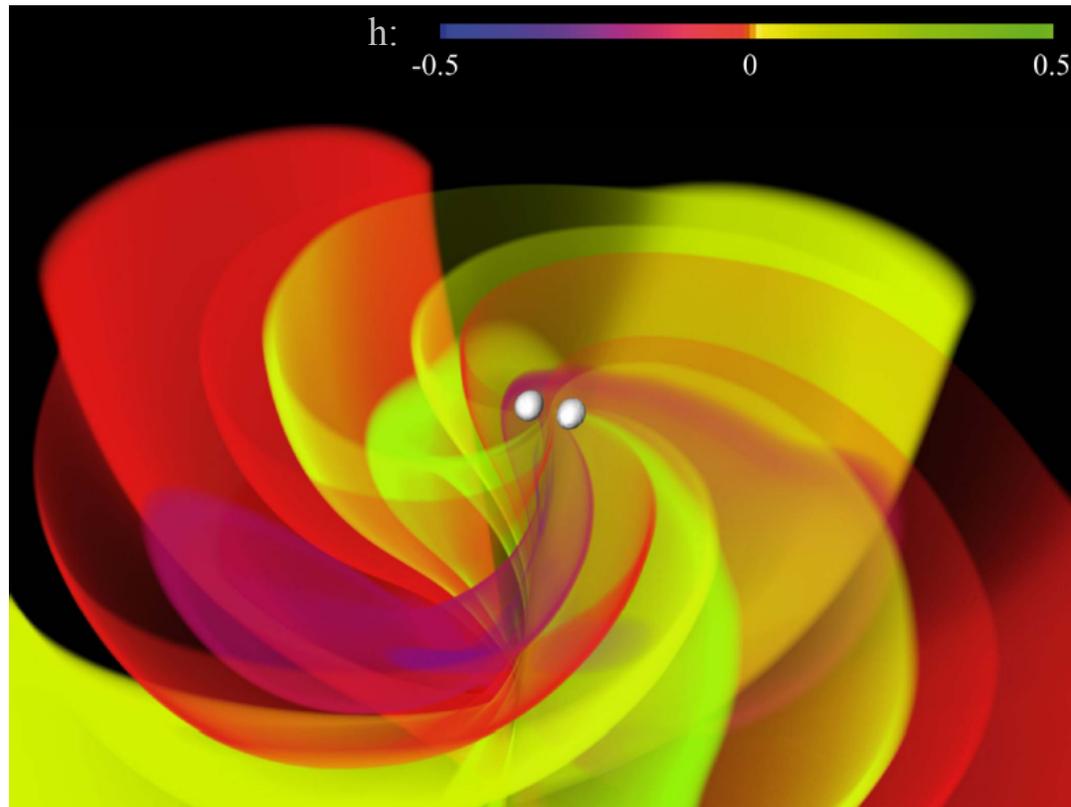


# Outline

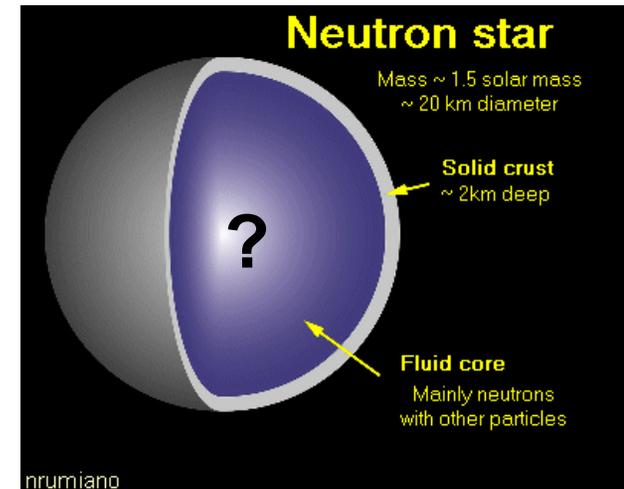
- Gravitational Waves
- Squeezed Light generation
- Sensitivity improvement of GEO600 with squeezed light
- Squeezed light as a key-technology for GW astronomy



# Merging Neutron Stars



**Merging neutron stars.** Numerical relativity simulation of the gravitational wave amplitude emitted from two neutron stars which are about to merge in 4 ms [Rezzolla, AEI].



**Gravitational wave astronomy requires observatories that can detect**

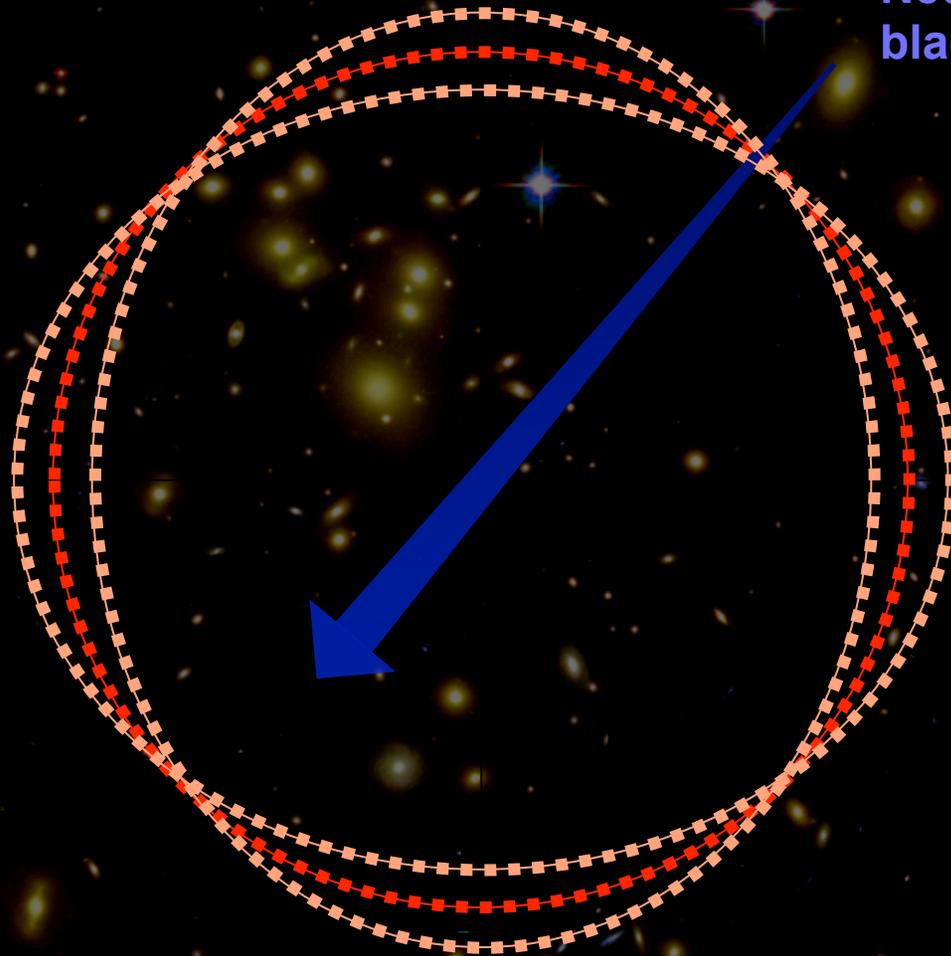
$$h < 10^{-23}$$

**(over a band from e.g. 100Hz - 200Hz)**



# Gravitational Waves

Neutron-star or  
black-hole binary



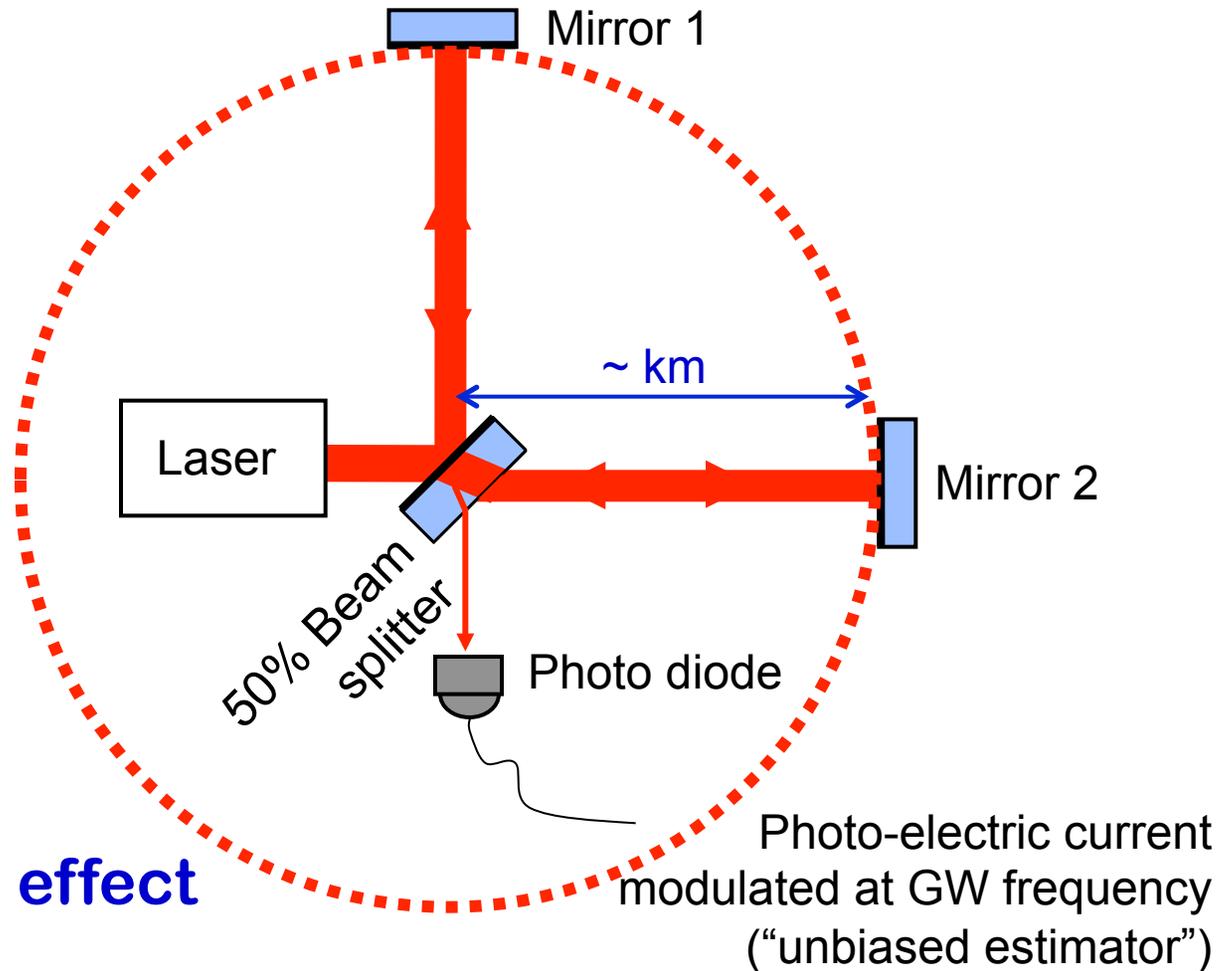
# Gravitational Wave Detection

1) Test masses

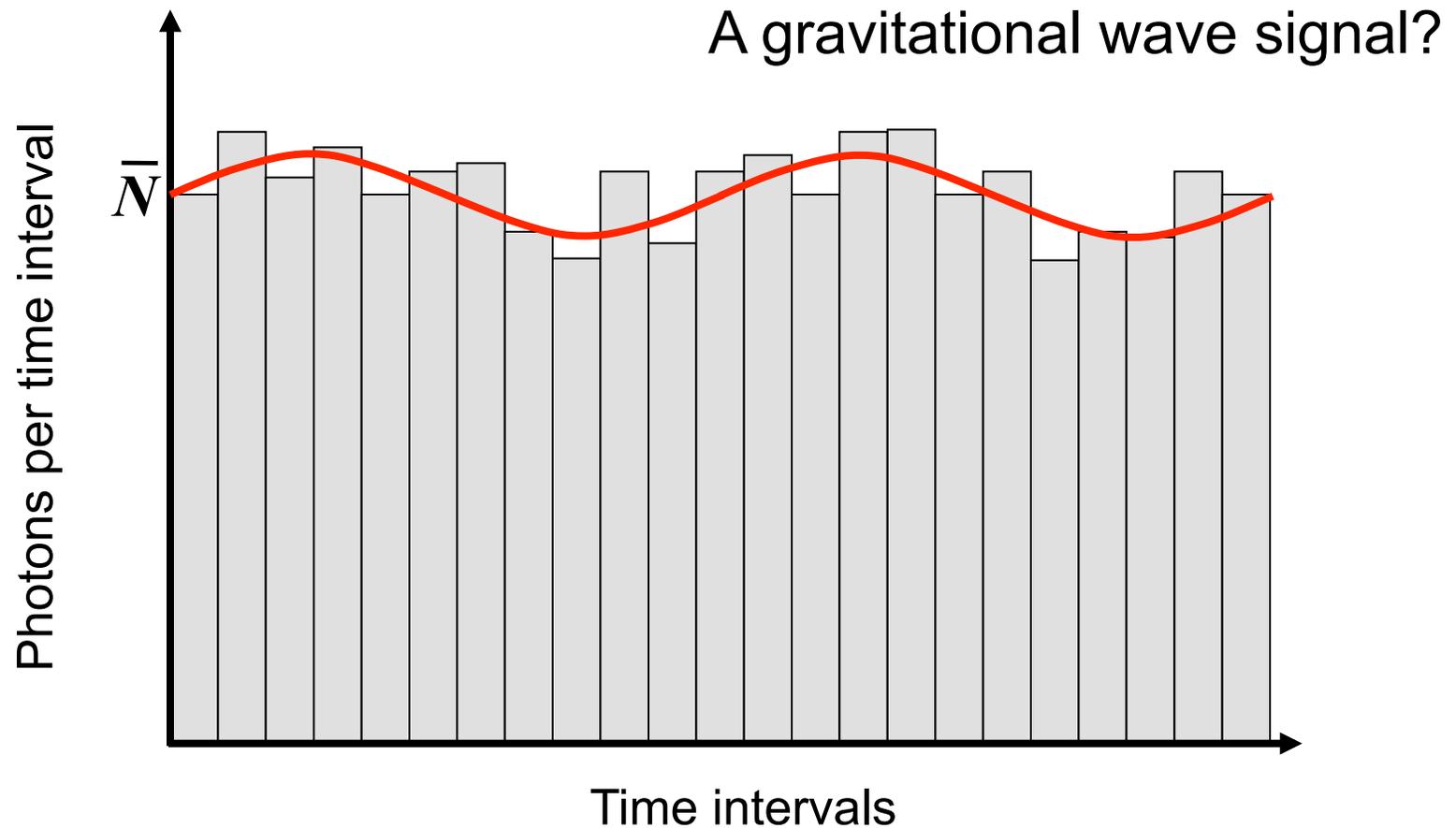
2) Laser light

3) Interference

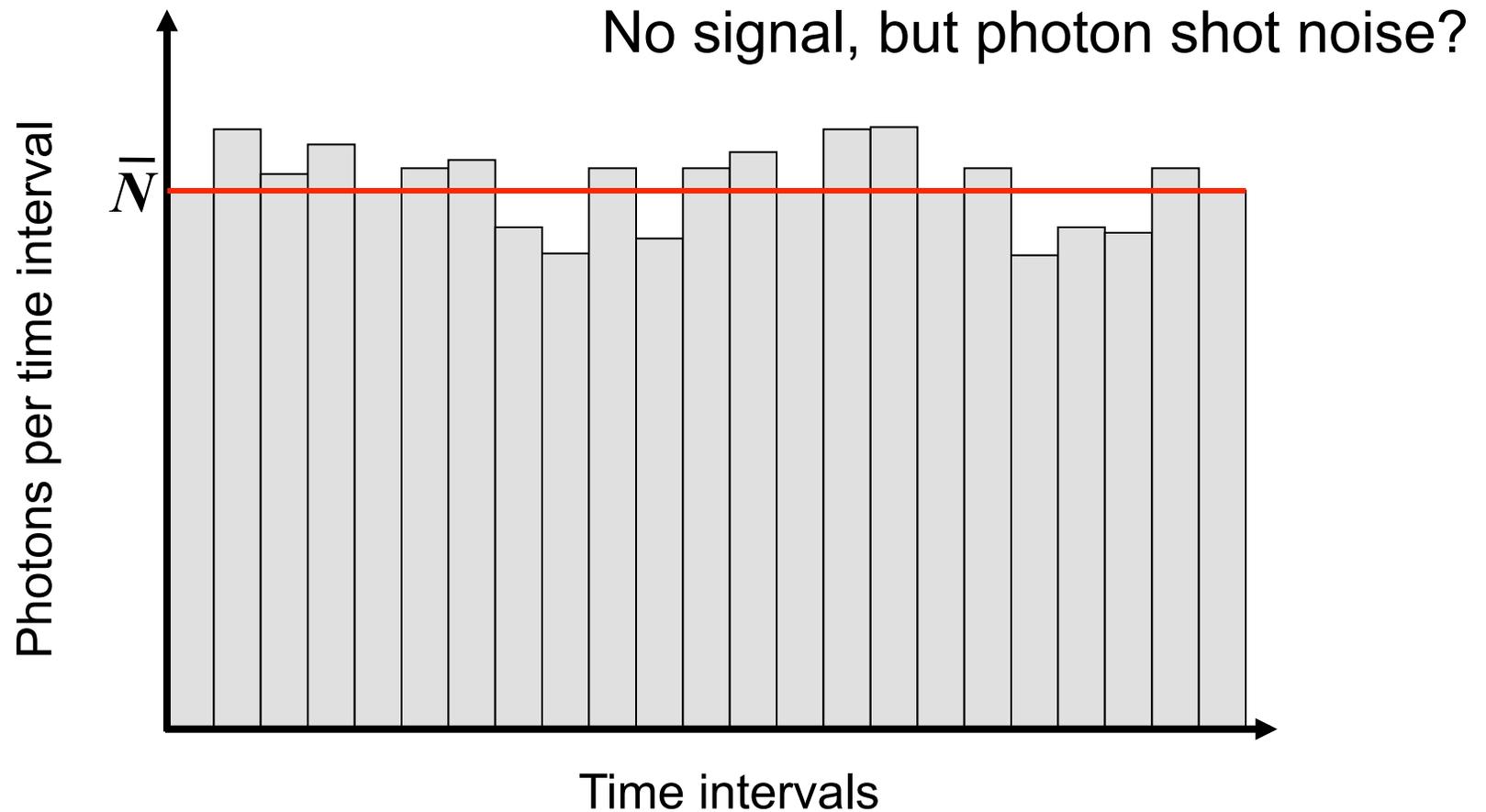
4) Photo-electric effect



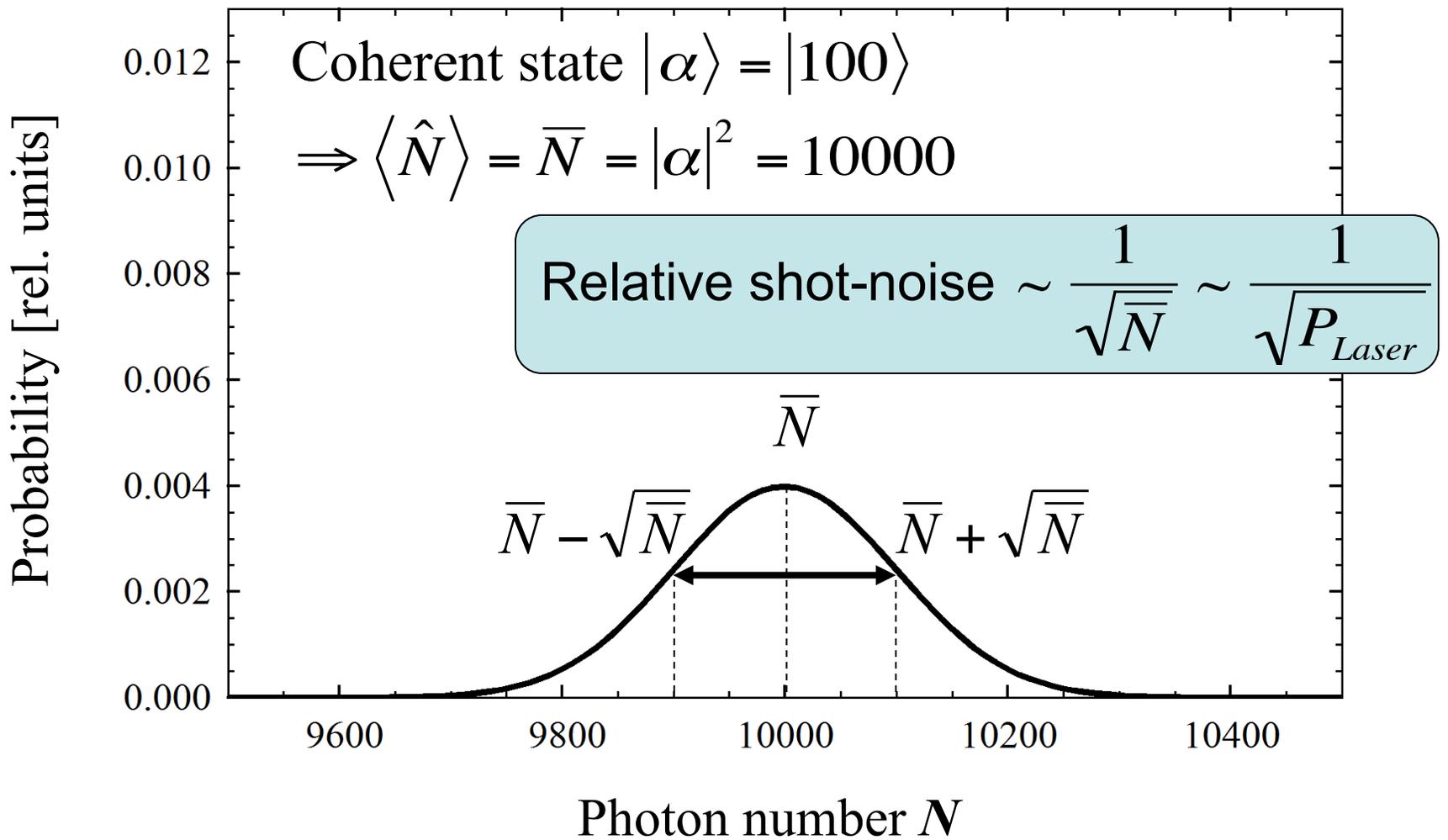
# Photo-Electric Current



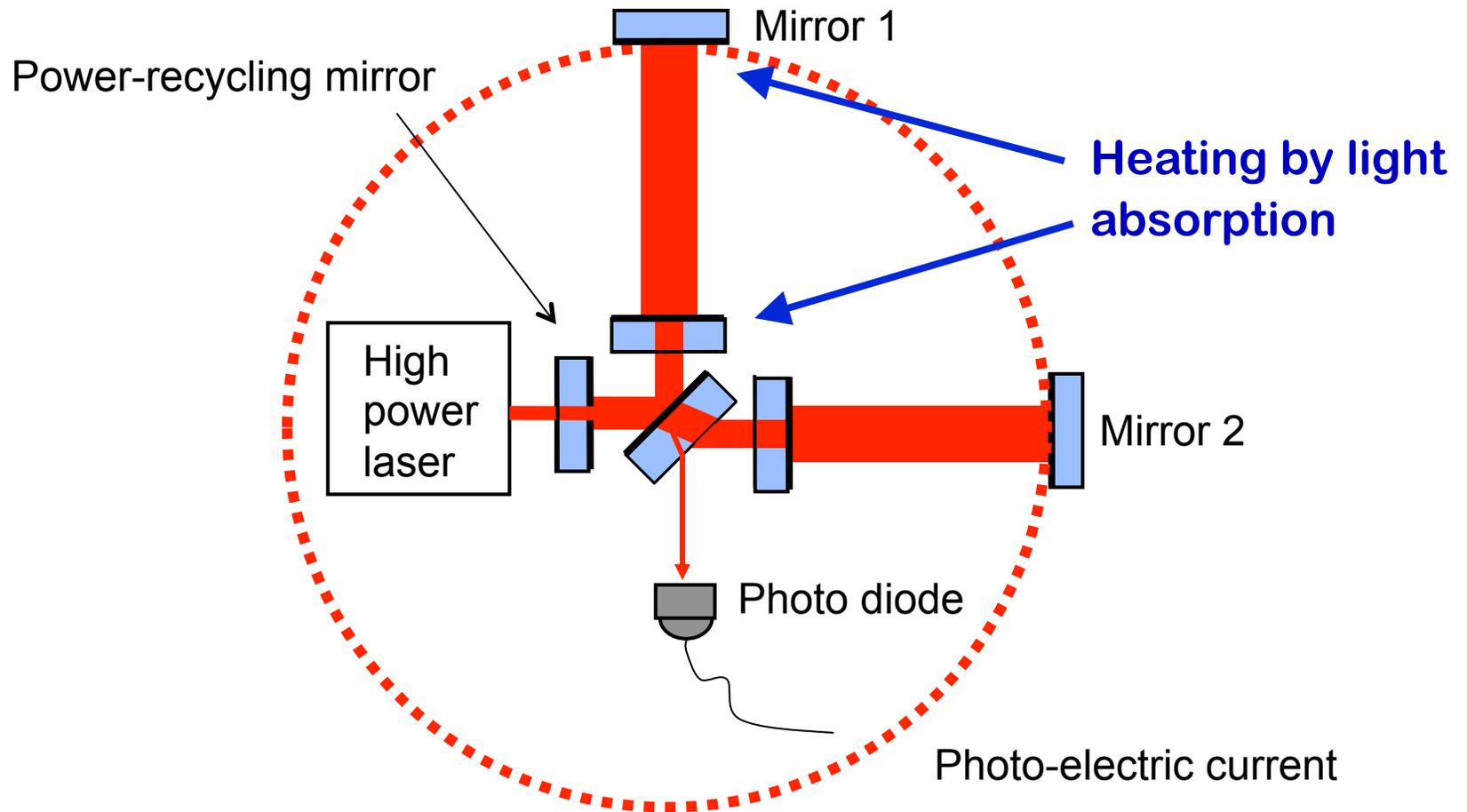
# Photo-Electric Current



# Photon Counting Statistics



# Increasing the Light Power



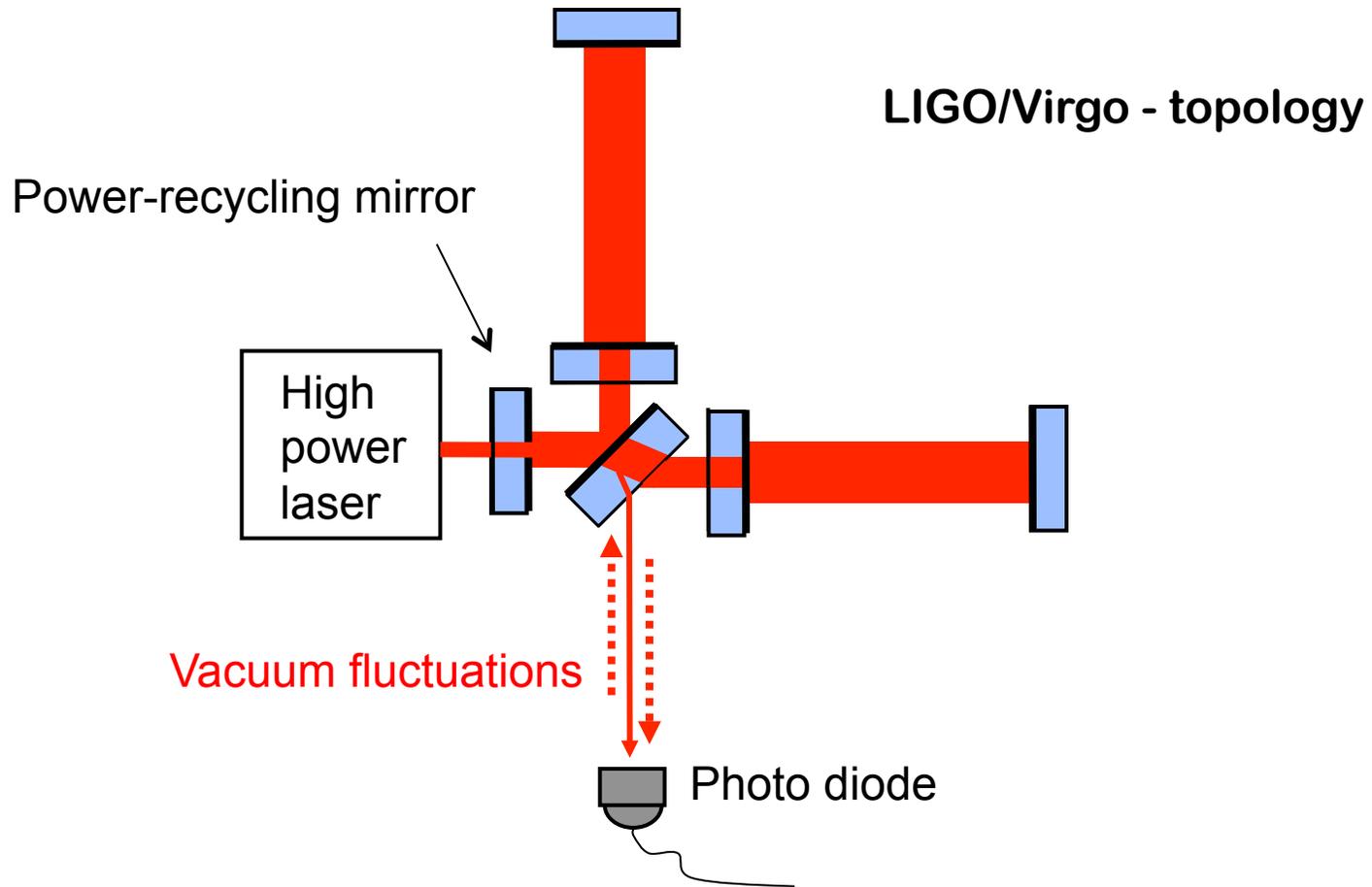
**Is there a possibility to increase  
the signal/quantum noise-ratio  
without increasing the laser power?**

**Yes, by squeezed light!**

[Caves, Phys. Rev. D 23, 1693 (1981)]



# Shot-Noise / Vacuum Fluctuations

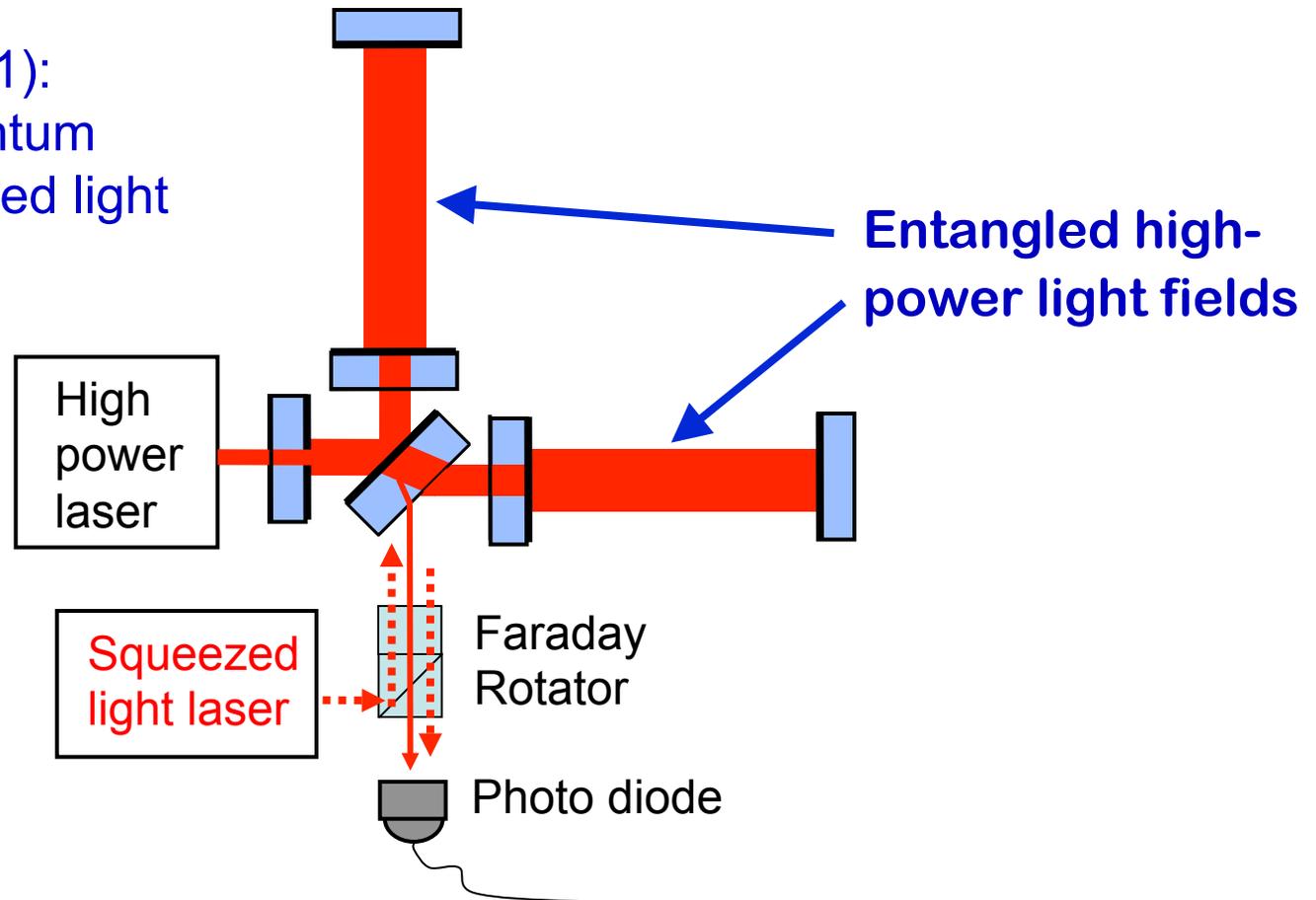


[Caves, Phys. Rev. D 23, 1693 (1981)]



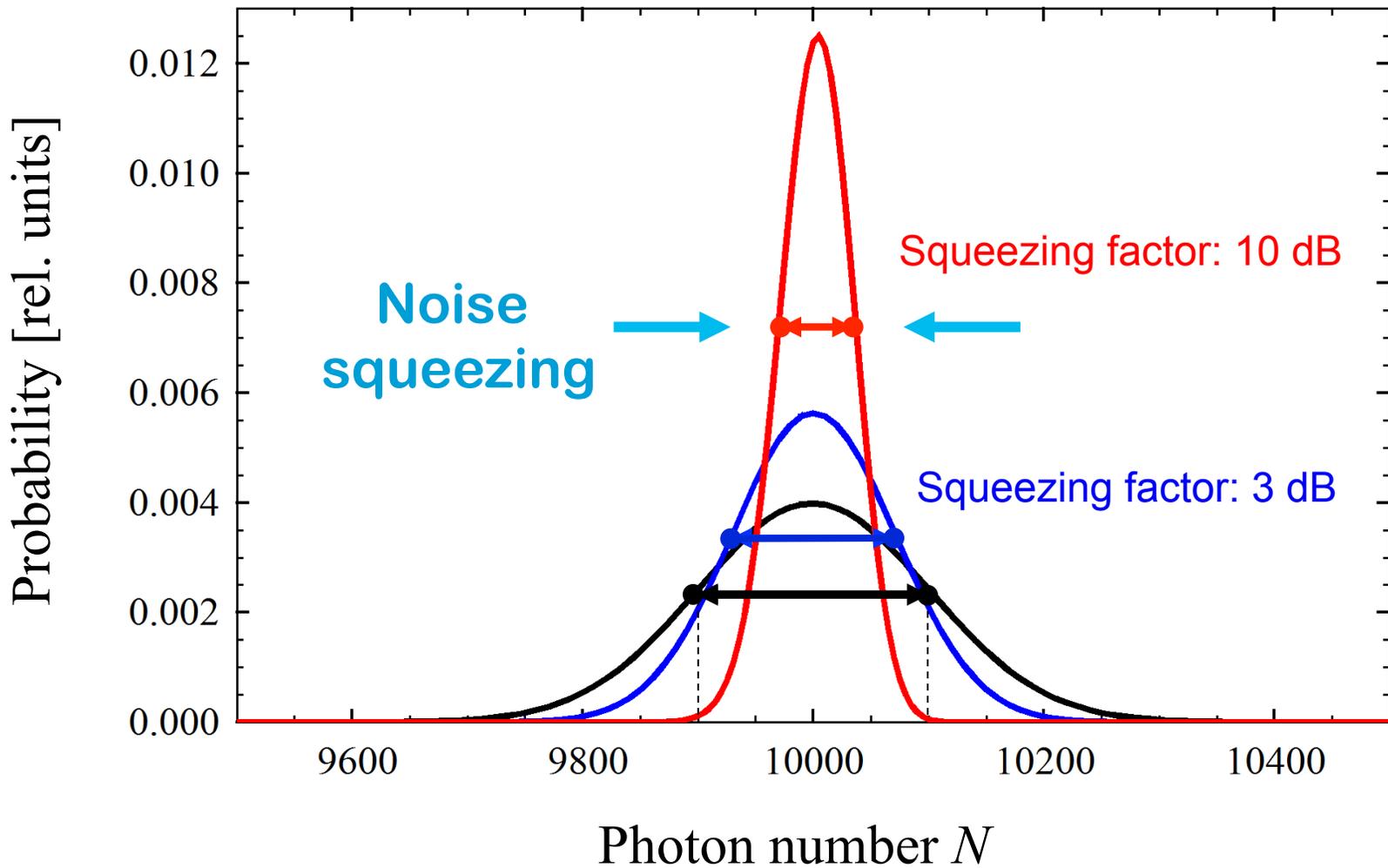
# Squeezing the Shot-Noise

C. M. Caves (1981):  
Reduction of quantum  
noise with squeezed light

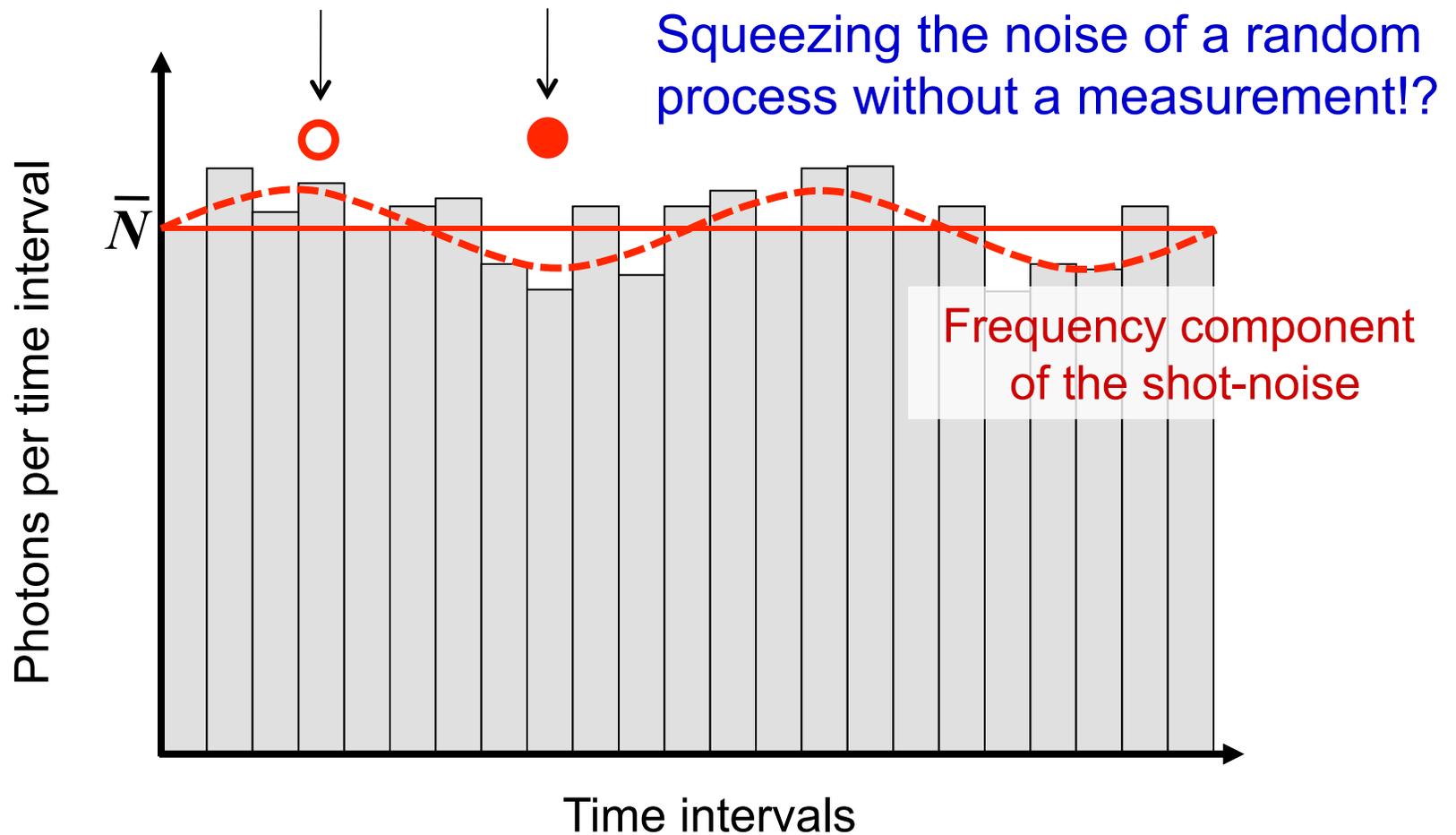


[Caves, Phys. Rev. D 23, 1693 (1981)]

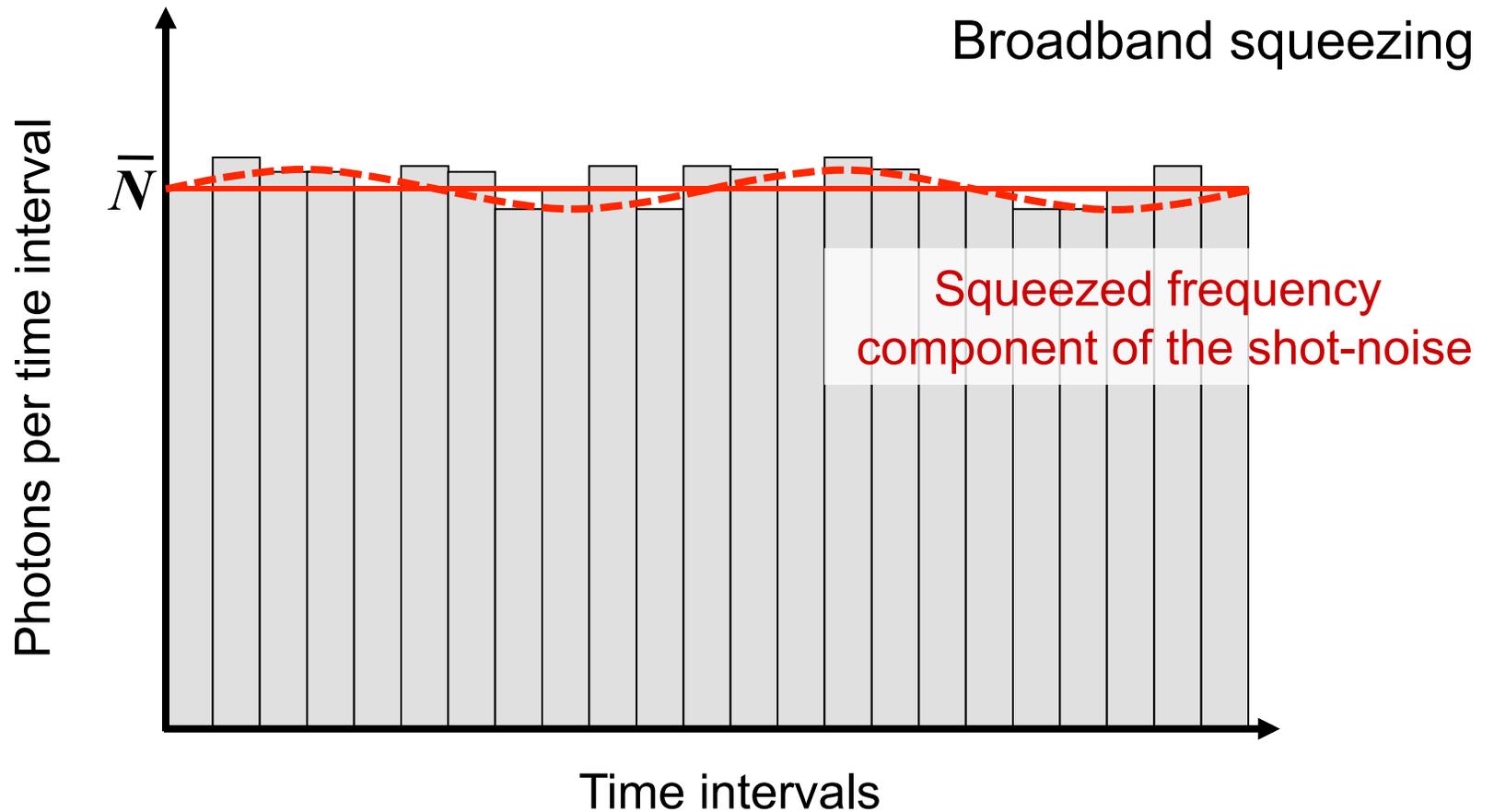
# “Squeezed” Counting Statistics



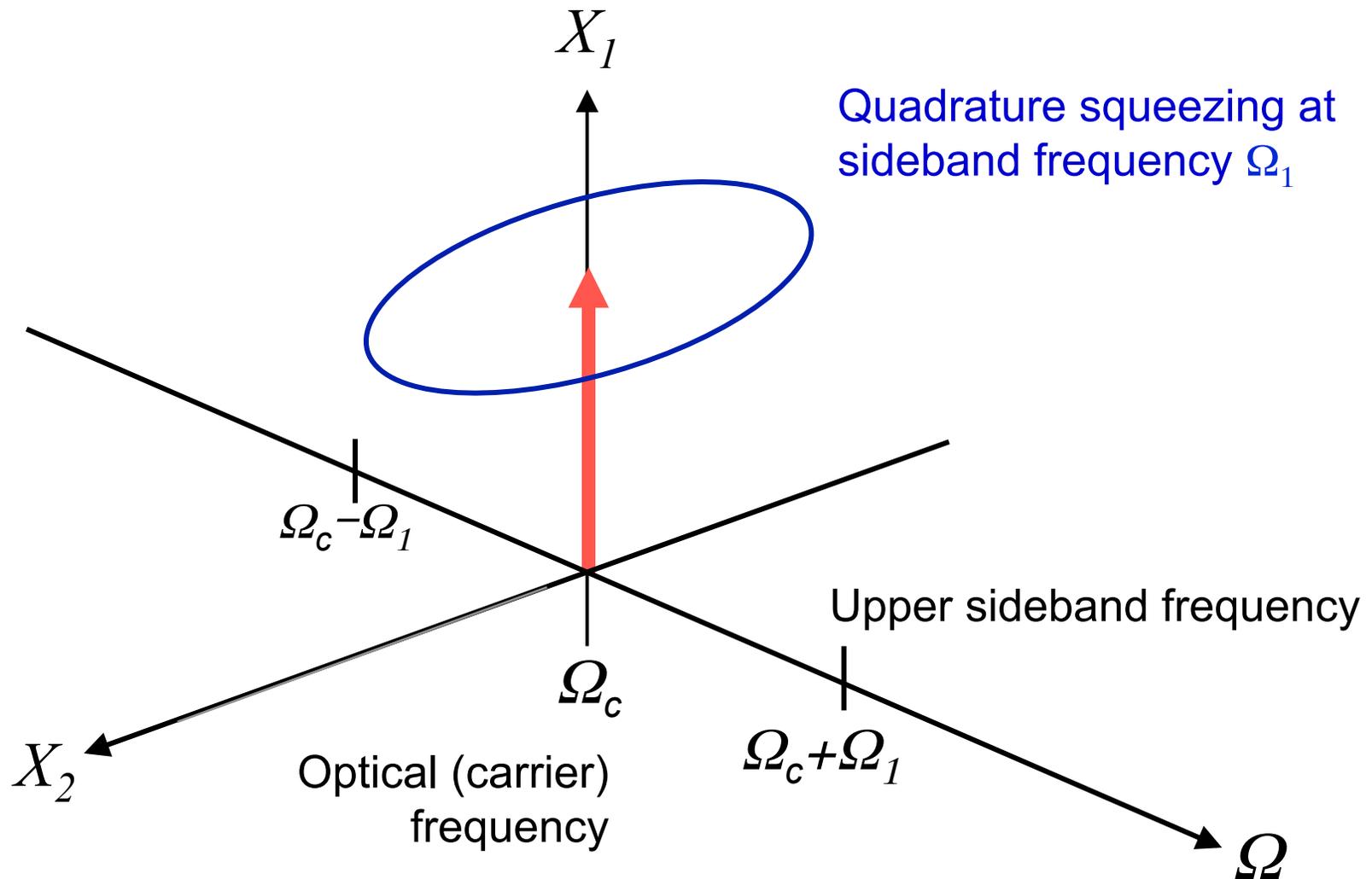
# Shot-Noise / Vacuum Fluctuations



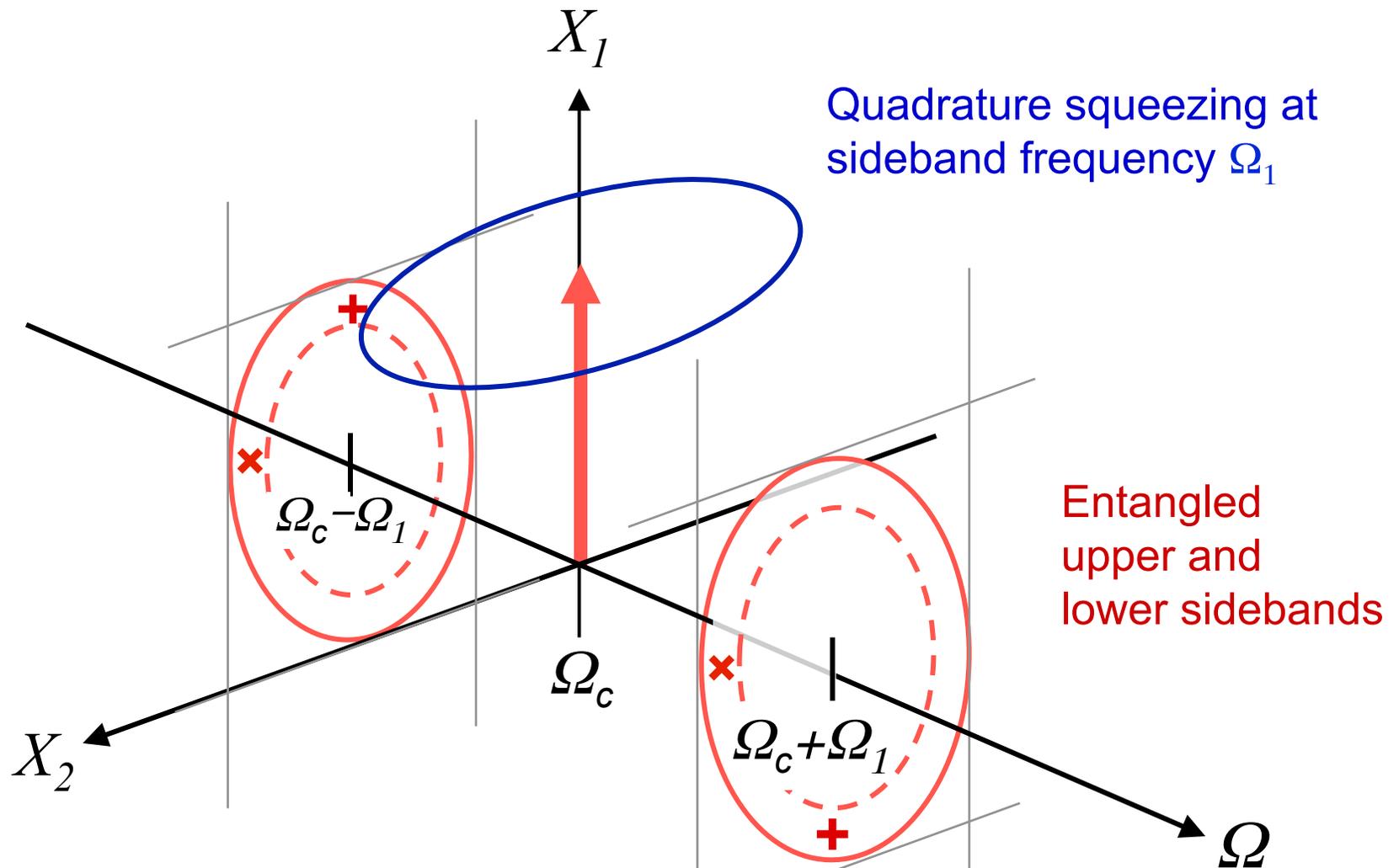
# Squeezed Shot-Noise



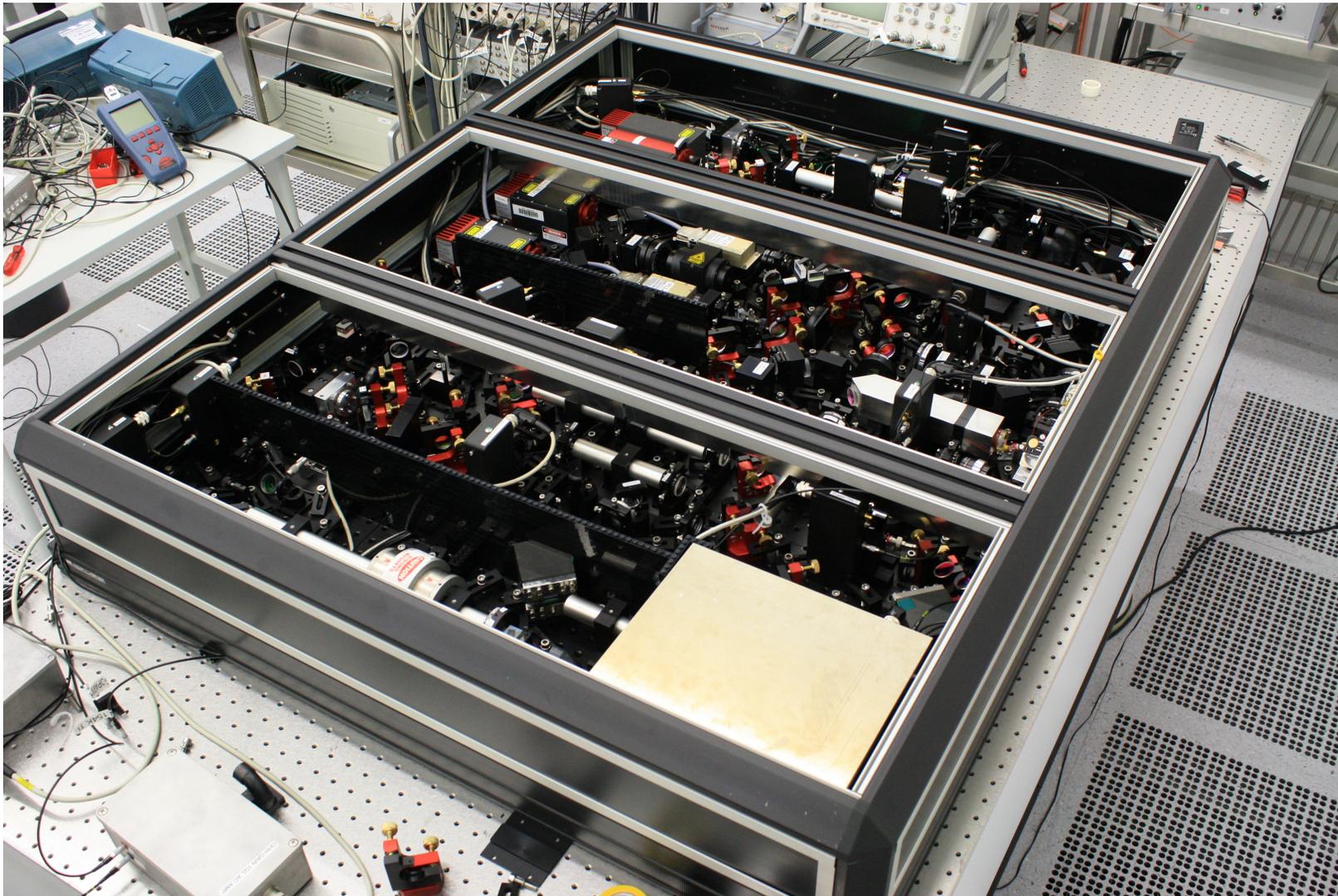
# Squeezing in the Wave Picture



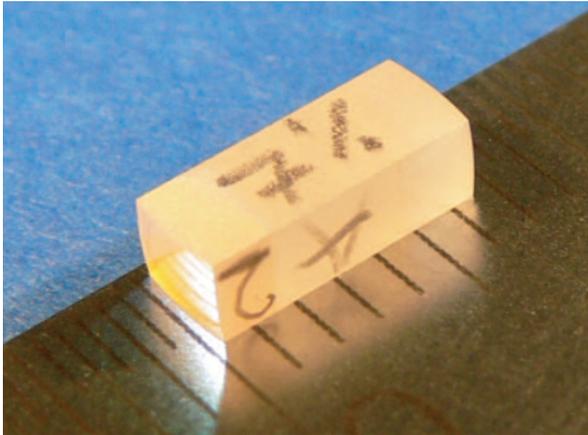
# Squeezing in the Wave Picture



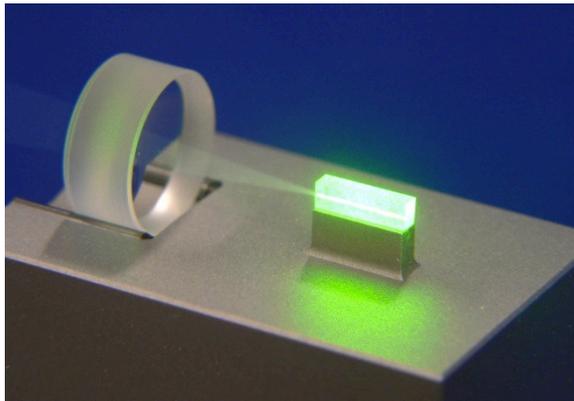
# The GEO600 Squeezed Light Laser



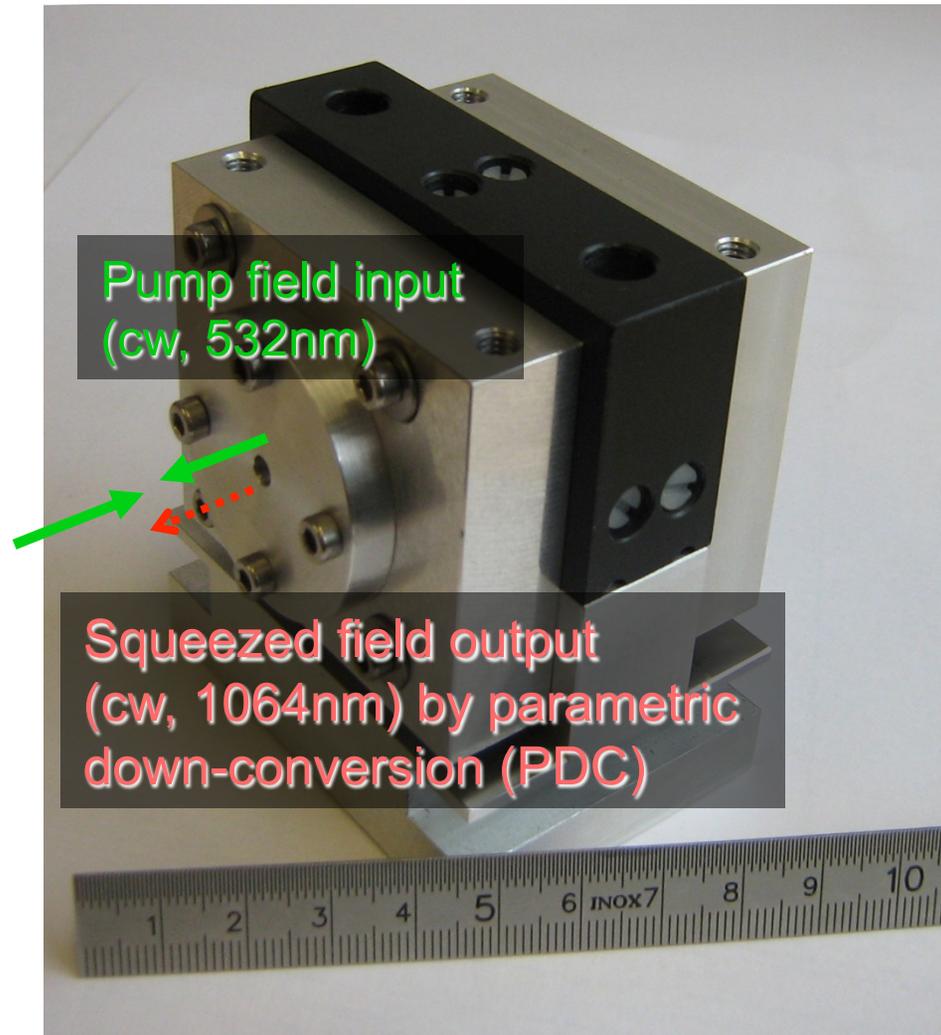
# Generation of Squeezed Light (PDC)



$\chi_2$ -nonlinear crystal:  
MgO:LiNbO<sub>3</sub> or PPKTP



Standing wave cavity



# History of Squeezed Light Generation

First squeezed light: [Slusher *et al.*, PRL **55**, 2409 (1985)]

Research labs with squeezed light (not complete):

- Kimble (CalTech): *teleportation*: [Furuzawa *et al.*, SCIENCE **282**, 706 (1998)]
- Grangier (Orsay); *kitten*: [Ourjoumtsev *et al.*, SCIENCE, **312**, 83 (2006)]
- Schiller and Mlynek (Konstanz): *tomography*: [Nature **387**, 471 (1997)]
- Bachor and Lam (Canberra): *6dB at 1064nm* [J. Opt. B **1**, 469 (1999)]
- Leuchs (Erlangen); *~7 dB pulsed* [Opt. Lett. **33**, 116 (2008)]
- Polzik (Copenhagen), [Neergaard-Nielsen *et al.*, PRL **97**, 083604 (2006)]
- Furusawa (Tokyo); *9 dB*: [Takeno *et al.*, Opt. Express **15**, 4321 (2007)]
- Fabre (Paris); Zhang, Peng (Shanxi); Andersen (Copenhagen); Mavalvala (MIT)
- Nussenzeig (Sao Paulo); Pfister (Virginia); ...



# Squeezing Issues for GW Detection

## Squeezing at frequencies in the GW detection band (10 Hz to 10 kHz)

- Control beam as noise source identified [Bowen, RS *et al.*, J. Opt. B **4**, 421 (2002)], [RS *et al.*, Opt. Comm. **240**, 185 (2004)]
- First Audioband squeezing [McKenzie *et al.*, PRL **93**, 161105 (2004)]
- New control scheme [Vahlbruch, RS *et al.*, PRL **97**, 011101 (2006)]
- 6 dB over complete band [Vahlbruch, RS *et al.*, NJP **9**, 371 (2007)]

## Compatibility with GW detector techniques

- Power-recycling [McKenzie *et al.*, PRL **88**, 231102 (2002).]
- Signal-recycling [Vahlbruch, RS *et al.*, PRL **95**, 211102 (2005)]
- Suspended interferometer [Goda *et al.*, Nat. Phys. **4**, 472 (2008).]

## Strong continuous wave squeezing (>10 dB) at 1064nm

- [Vahlbruch, RS *et al.*, PRL **100**, 033602 (2008)]
- [M. Mehmet, RS *et al.*, PRA **81**, 013814 (2010)]

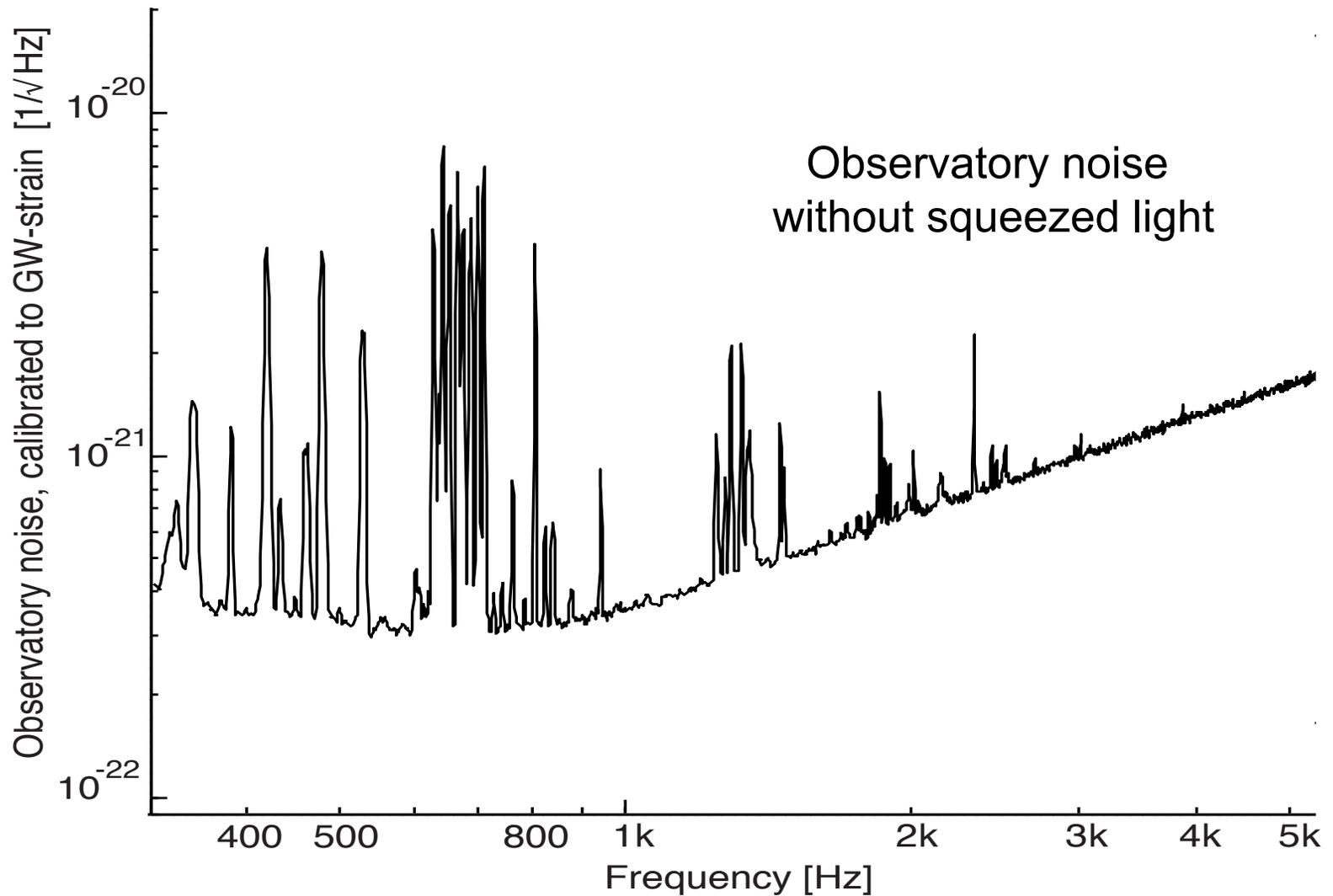
Review: [R.S. *et al.*, Nature Comm. 1:121 doi: 10.1038/ncomms1122 (2010)]



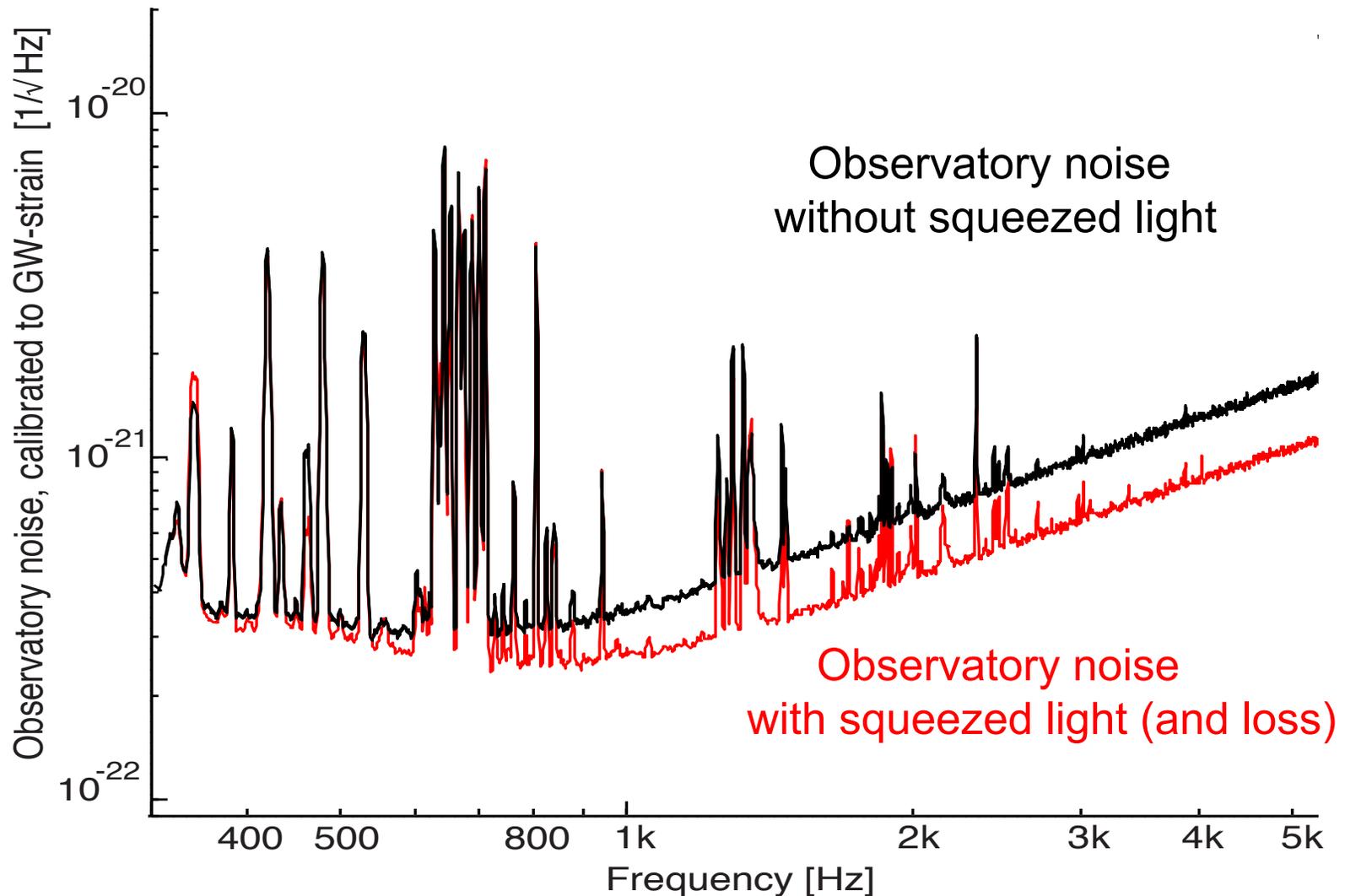
# Transport to the GEO600 GW Detector



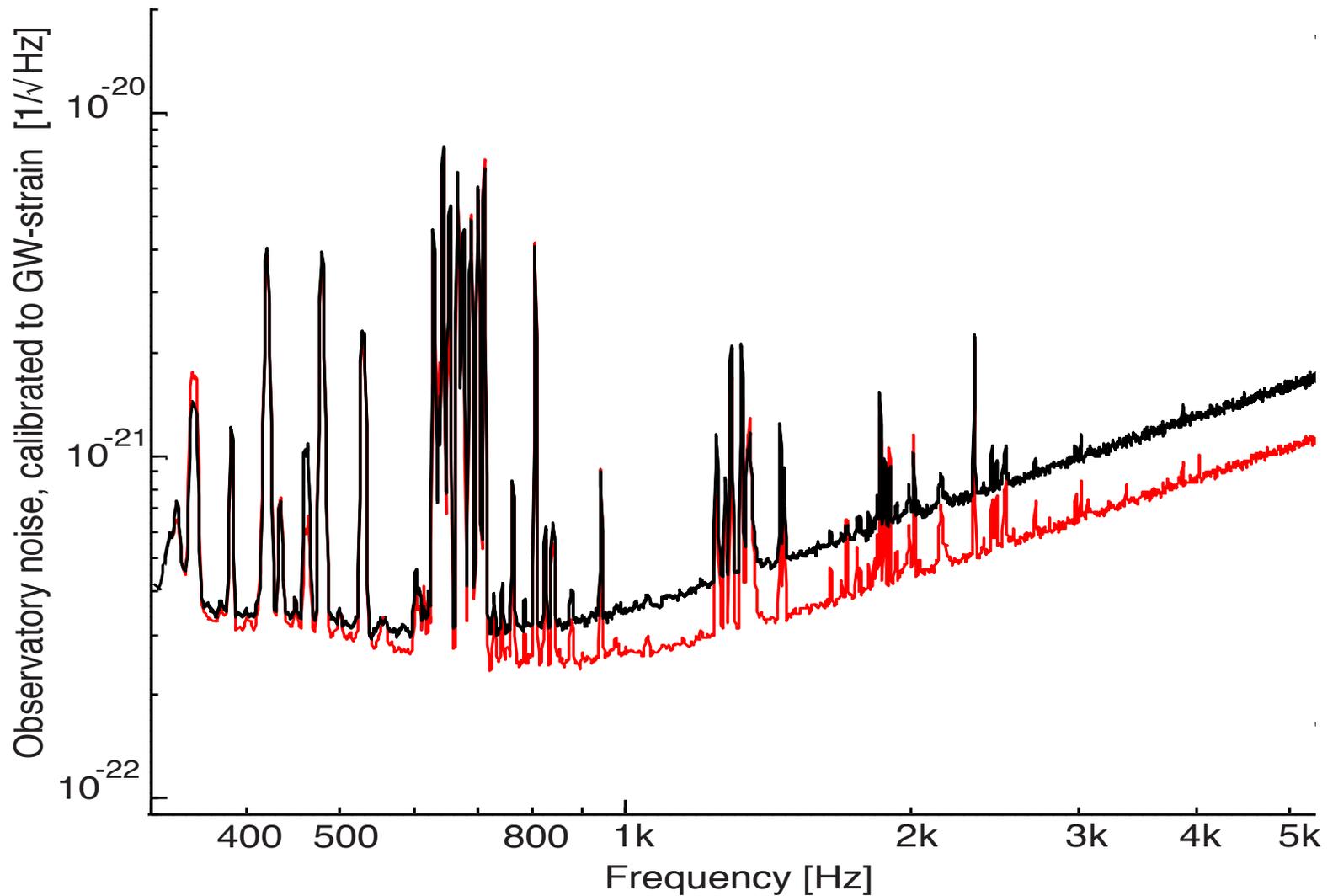
# GEO600: Its Lowest Noise Till 2010



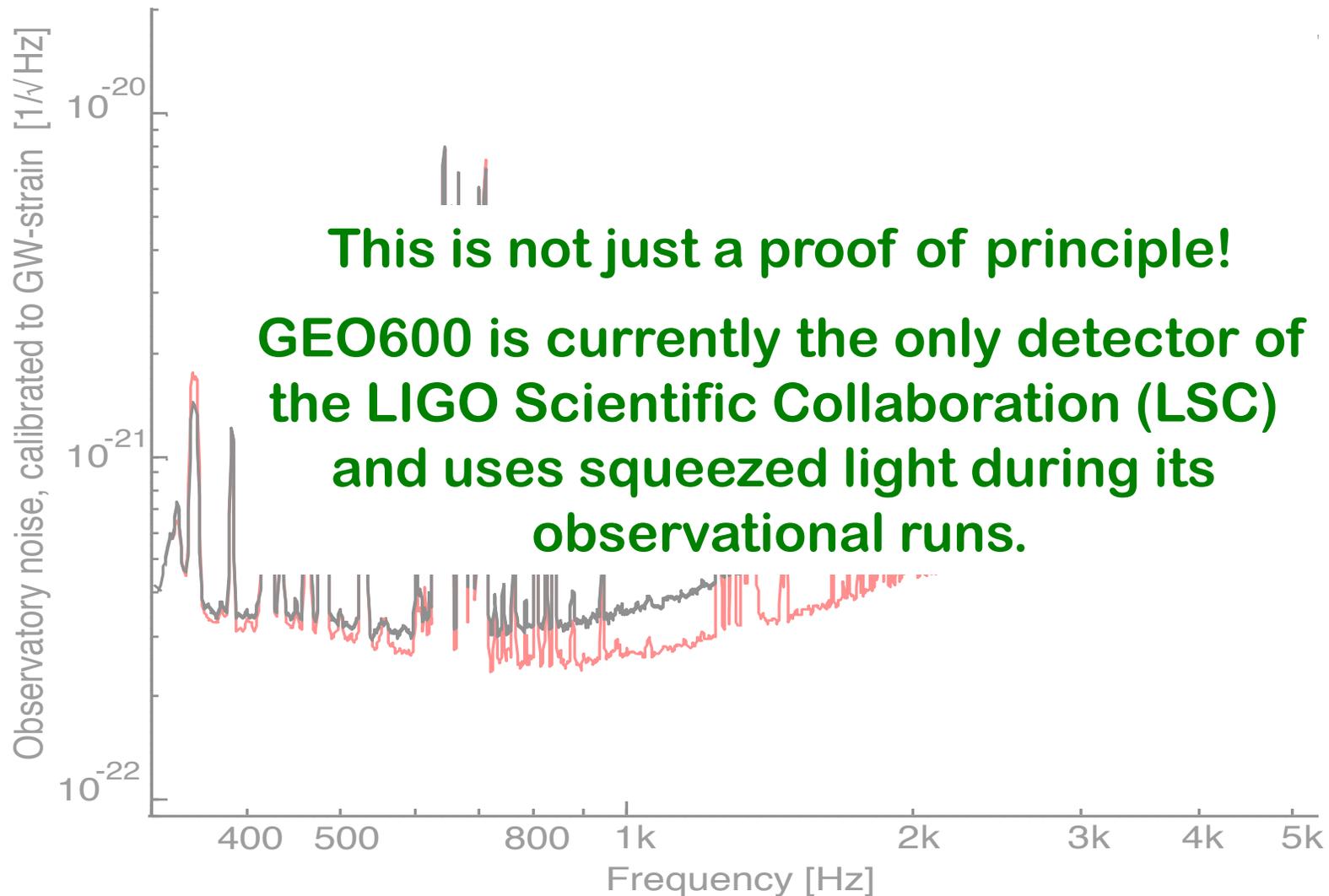
# GEO600: Squeezed Light in Application



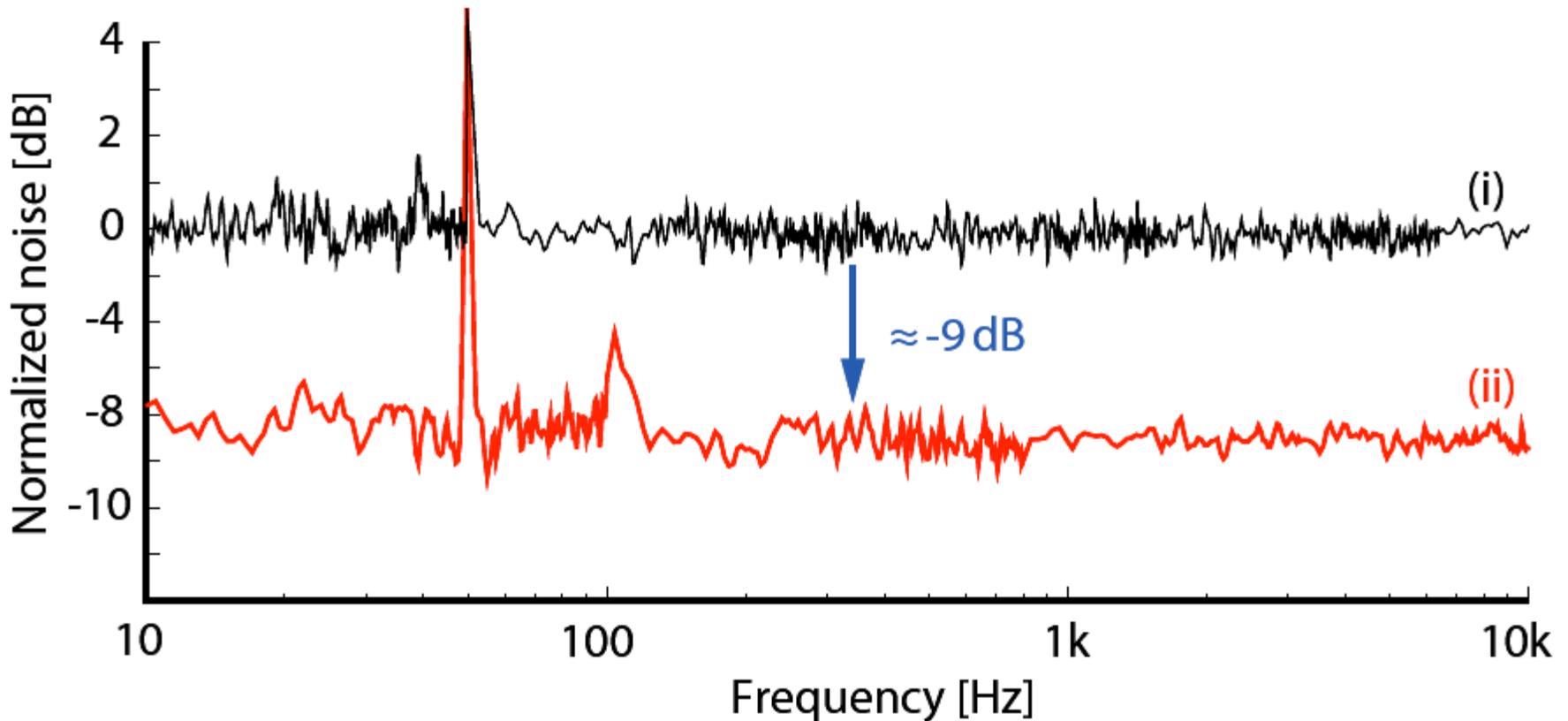
# GEO600: Squeezed Light in Application



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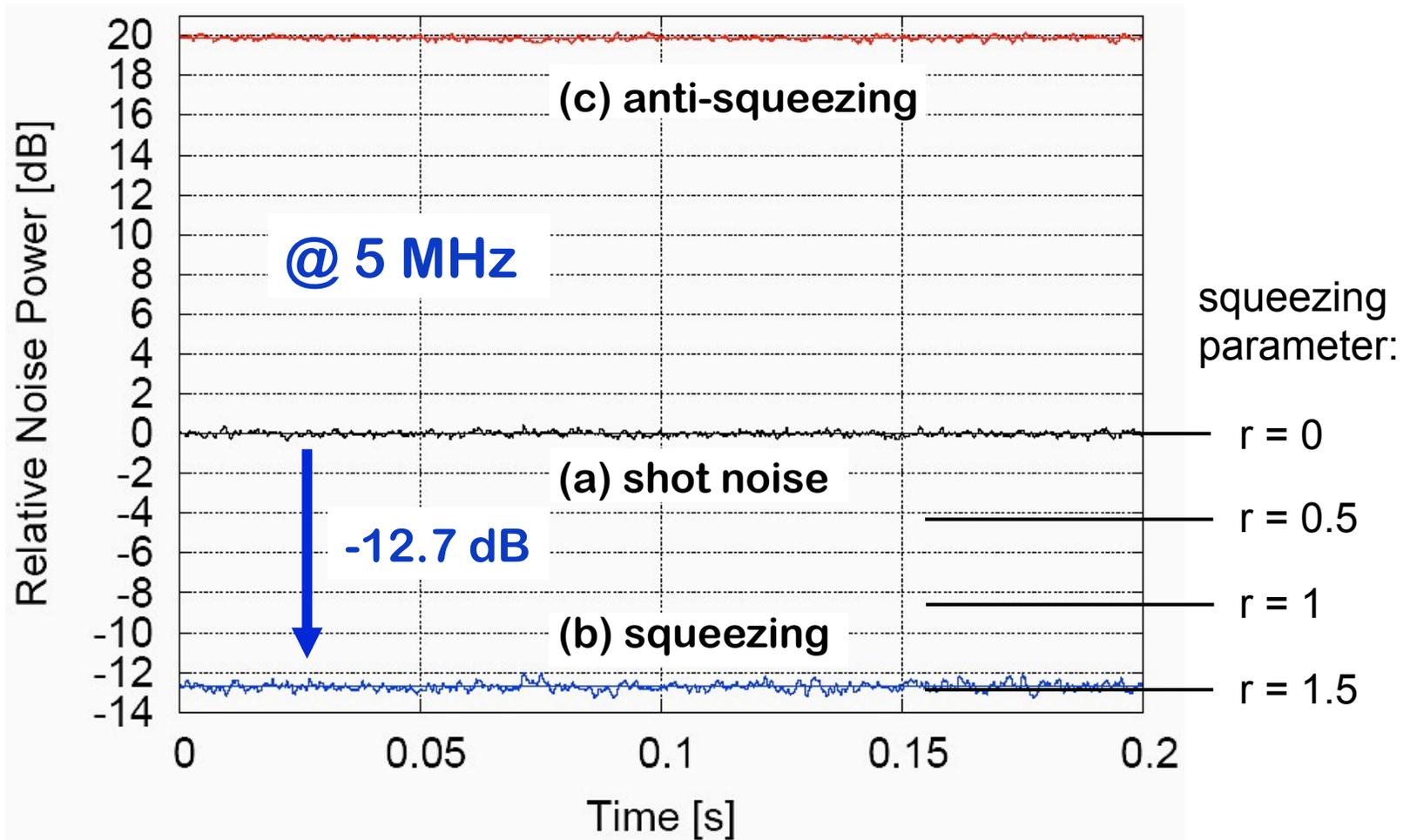
# The GEO600 Squeezed Light Laser



[H. Vahlbruch, A. Khalaidovski, N. Lastzka, C. Gräf, K. Danzmann, and R. Schnabel, *The GEO600 squeezed light source*, *Class. Quantum Grav.* **27**, 084027 (2010).]



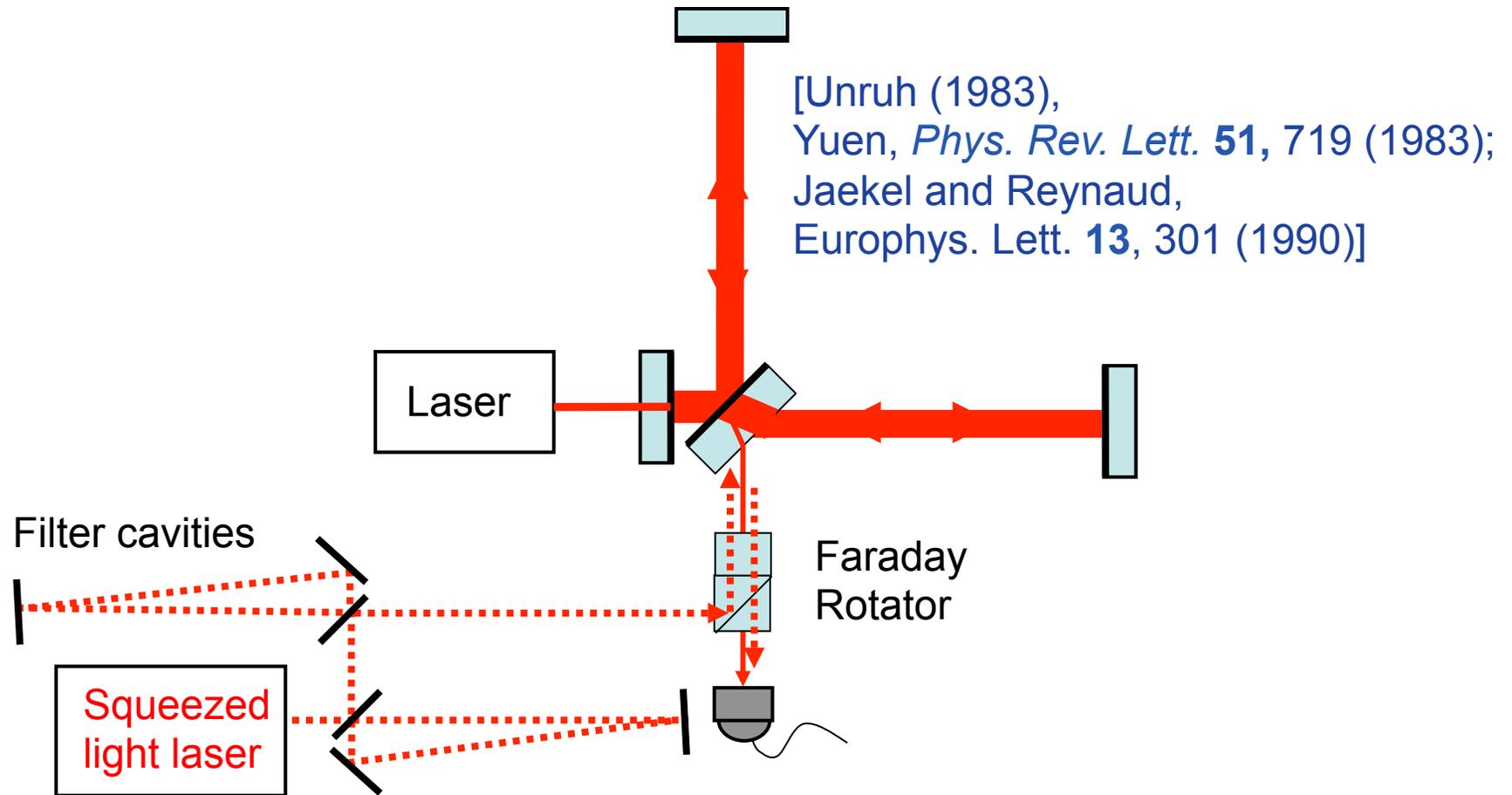
# 12.7 dB @1064 nm / 12.3 dB @1550 nm



[T. Eberle *et al.*, PRL **104**, 251102 (2010); M. Mehmet *et al.*, Opt. Exp. **19**, 25763 (2011)]



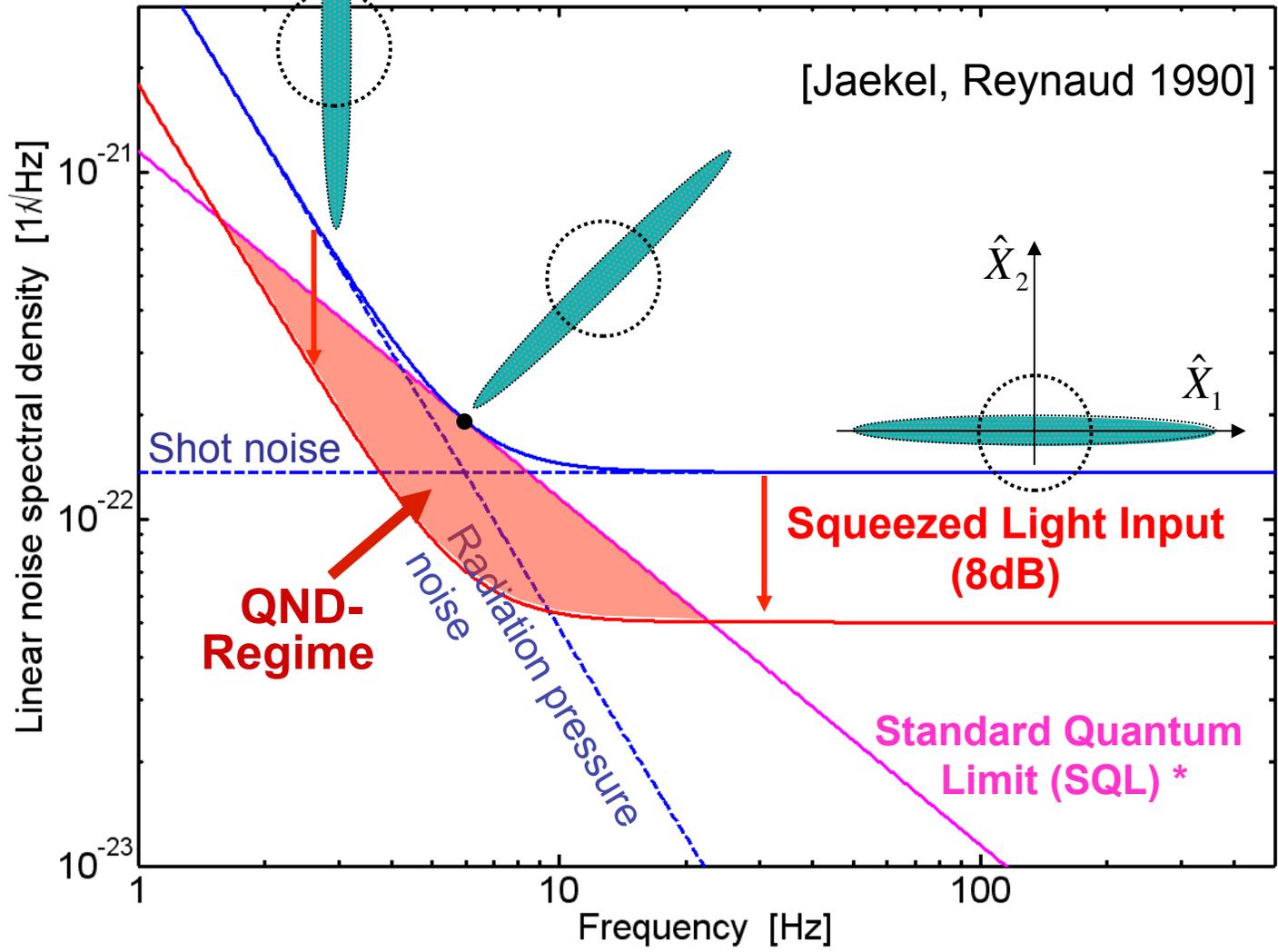
# Squeezing the Shot-Noise (SN) and the Radiation Pressure Noise (RPN)



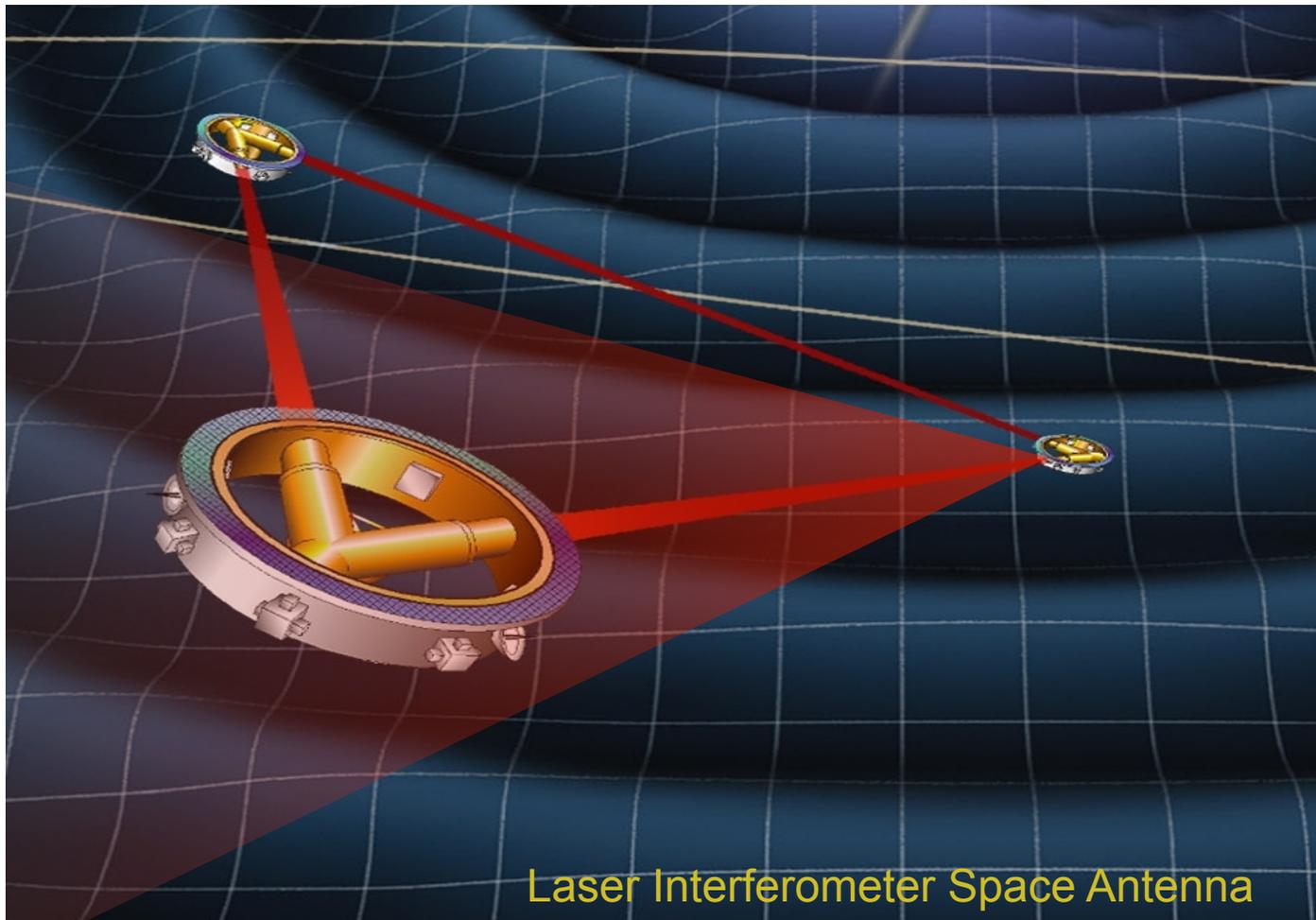
[Kimble *et al.*, *Phys. Rev. D* **65**, 022002 (2001)]



# Squeezing SN and RPN



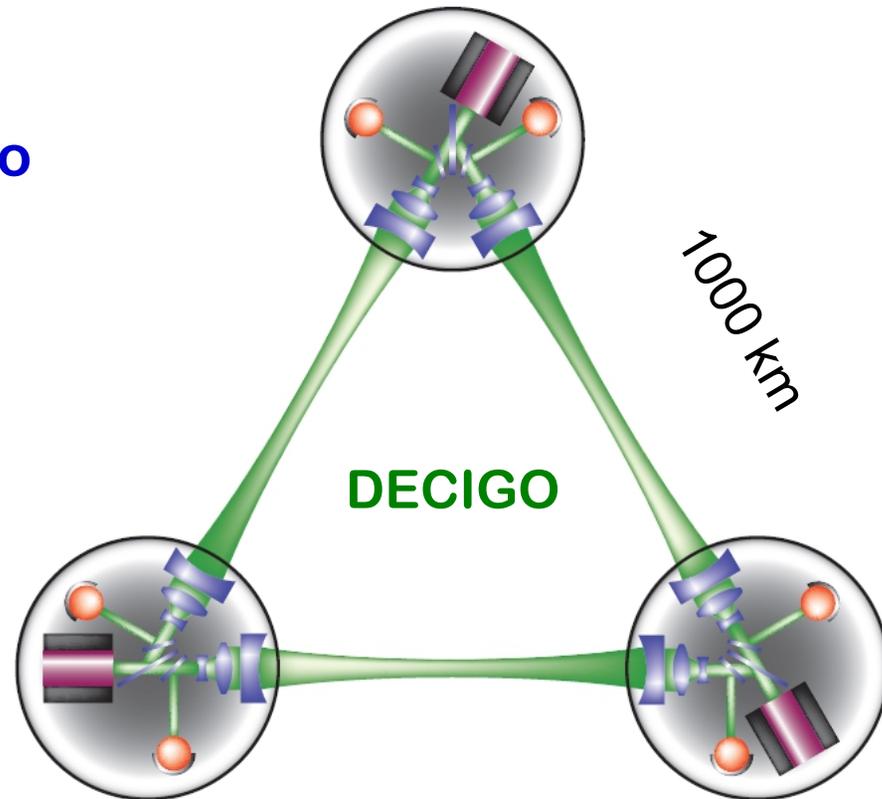
# Squeezed Light in Space ? Losses !



# Squeezed Light in Space ? Losses !

Less optical loss due to shorter arm length.

Squeezed light not considered yet, but conceivable.

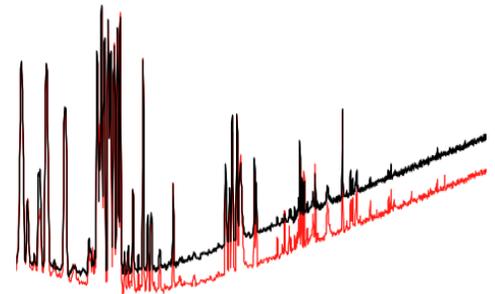
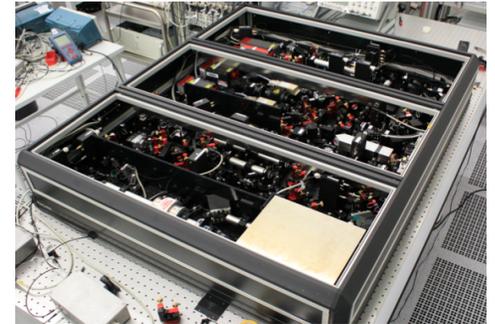


Japanese design study  
(0.1 Hz – 10 Hz, 1000 km long cavities, 532nm, heliocentric orbit)

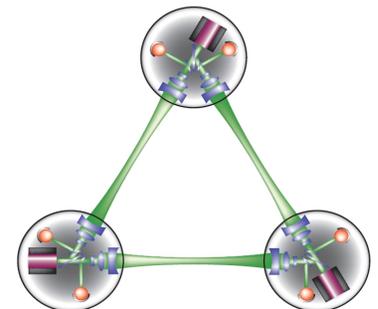


# Summary

- GEO600 uses squeezed light in observational runs and achieves its best ever sensitivity
- The improvement corresponds to 3.5 dB at shot-noise limited frequencies
- Up 12.7 dB of squeezing has been generated at 1064nm and 1550nm.
- *“Squeezed light might become a key-technology for GW detectors on ground and possibly even in space”*



Centre of Excellence:  
quantum engineering and space time research

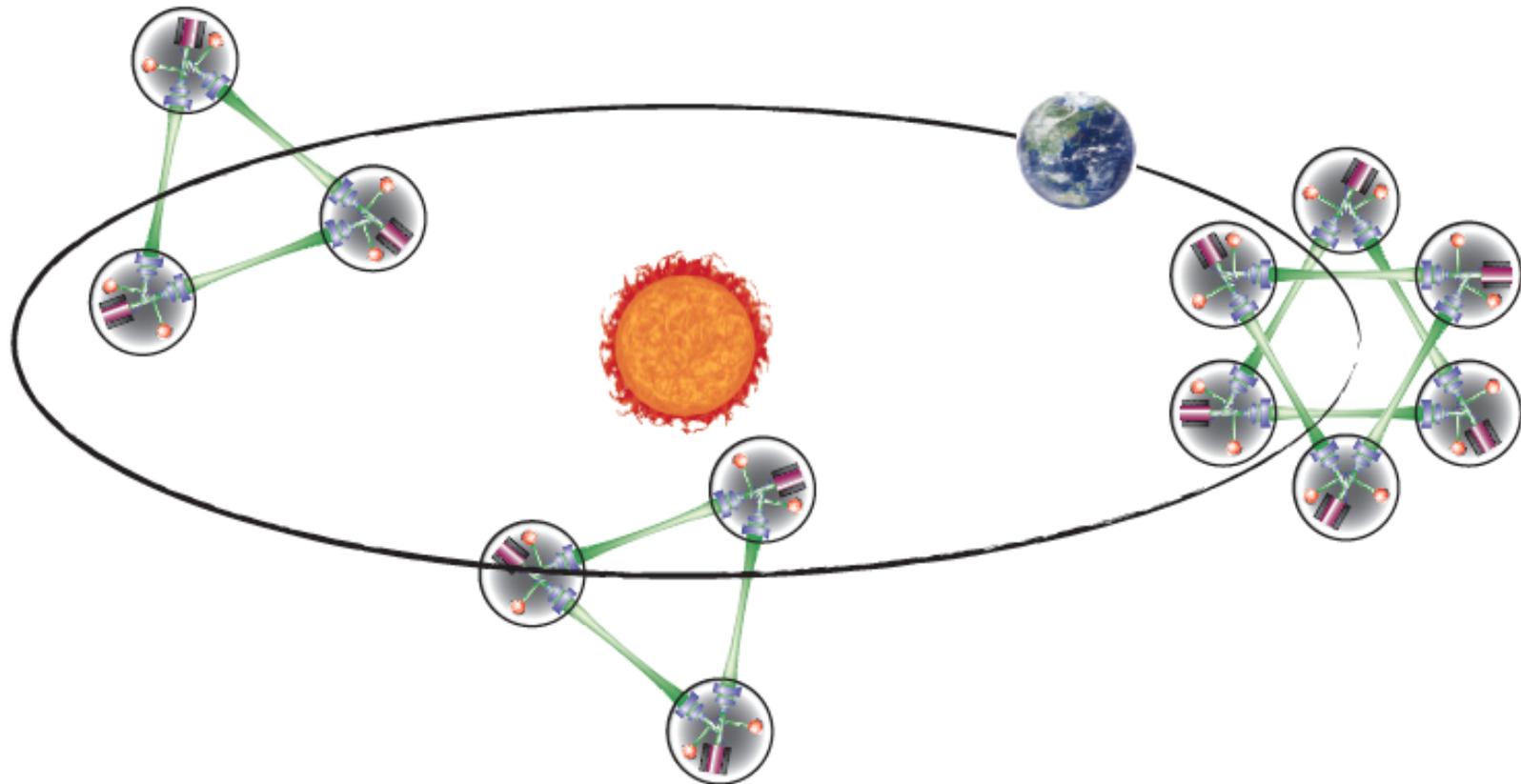


# PhD Students and Postdocs



# DECIGO

(DECi-hertz Interferometer  
Gravitational wave Observatory)



[S. Sato *et al.*, Journal of Physics: Conference Series **154**, 012040 (2009)]

